

ACTIVE COMPENSATING CAPACITIVE MULTIPLIER

Technical Field of the Invention

5 This invention relates to frequency compensation of electronic circuits, and more particularly relates to circuits having compensating capacitors, such as Miller Effect capacitors.

Background of the Invention

10 The stability performance of circuits having feedback is improved by providing compensation so as to increase phase margin. A well known technique for improving phase margin takes advantage of the Miller Effect, by adding a Miller-compensating capacitance in parallel with a gain stage, e.g., the output stage of a two stage amplifier circuit. Such a configuration results in the well-known and desirable
15 phenomenon called pole splitting, which advantageously multiplies the effective capacitance of the physical capacitor employed in the circuit. See, e.g., for background on compensation of amplifier circuits using Miller-compensating capacitance, Paul R. Gray and Robert G. Meyer, *Analysis and Design of Analog Integrated Circuits*, Third Ed., John Wiley & Sons, Inc., New York, 1993, Ch. 9,
20 especially pp. 607-623.

A problem arises when the load capacitance seen by a circuit having compensating capacitance such as Miller-compensating capacitance becomes large. This requires the compensating capacitance to increase in value in order to maintain stability. However, the larger compensating capacitance occupies more physical
25 space. But, this is not a luxury that can be afforded in an environment where more circuits are integrated onto the same die, which, of course, is the trend.

There is thus a need for a way of dealing with larger load capacitance seen by amplifier circuits having compensating capacitance such as Miller-compensating

capacitance, without placing increasing demands on die area for the circuit. There is also a need to optimize and reduce the silicon area requirement of existing circuit designs using such capacitors, to allow greater chip packing densities, and thus single integrated chip solutions.

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Summary of the Invention

5 The present invention provides an improved compensated amplifier, for amplifying an input signal applied to an input node to provide an output signal at an amplifier output node. The compensated amplifier includes a first amplifier stage having an internal node functioning as an input thereto and having a first stage output node. Also included is a second amplifier stage coupled to the first amplifier stage, having the input node as an input thereto and providing the output signal at the amplifier output node. A capacitor is coupled between the output node and the
10 internal node.

The invention may be advantageously applied for the purpose of multiplying Miller-compensating capacitance, although it is not limited to that application.

15 It is to be understood that the term "amplifier" as used herein is not limited to any specific form of amplifier, such as an operational amplifier. Rather, the term is intended to refer to any circuit that provides an amplified form of an input signal applied thereto.

20 These and other features of the invention will be apparent to those skilled in the art from the following detailed description of the invention, taken together with the accompanying drawings.

Brief Description of the Drawings

Fig. 1 is a schematic diagram of a prior art differential amplifier including a Miller-compensating capacitor.

5 Fig. 2 is a schematic diagram of a differential amplifier including a Miller-compensating capacitor provided in accordance with the principles of the present invention.

Fig. 3 is a diagram showing an ac-equivalent circuit model of the amplifier circuit of Figure 2.

10 *201* Fig. 4 is a schematic diagram of a simple amplifier including a compensating capacitor provided in accordance with the principles of the present invention.

Fig. 5 is a diagram showing an ac-equivalent circuit model of the amplifier circuit of Figure 4.

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Detailed Description of the Preferred Embodiment

Figure 1 is a schematic diagram of a prior art differential amplifier 10 including a Miller-compensating capacitor C1. A supply voltage V_{DD} is provided between a supply rail 12 and a ground rail 13. A sinking bias current i_B is provided on an input line 14. A differential input is provided, with the positive going signal V_p being provided on input line 16 and the negative going signal V_n being provided on input line 18. The amplifier 10 structure is two stage. The first stage 20 is a folded-cascode differential amplifier. The second stage 22 is a Miller-compensated PMOS device amplifier.

In the first stage 20, the differential inputs on lines 16 and 18 are provided to the respective gates of a pair of PMOS devices 24, 26. The differential current generated through devices 24, 26, is reflected into NMOS devices 28, 30. The voltage on the drain of device 30 is sensed at the gate of output PMOS device 32. Capacitor C1 and resistor R1, series connected between the drain and gate of device 32, provide Miller compensation for amplifier 10.

The other circuitry of amplifier 10 is provided for the various biases required by amplifier 10. Thus, NMOS device 34 provides a quiescent bias current for output PMOS transistor 32. PMOS device structure 38 is a multiple output current mirror. Device 40 is diode-connected and establishes a stable internal bias voltage, based on the input bias current i_B on line 14. This stable bias current i_B is thus mirrored by devices 42, 44, 46, and 48. The mirrored current in device 42 is converted into another stable bias voltage by NMOS device 50 at node 52, which biases the gates of devices 28, 30. The mirrored current in device 44 is also mirrored by NMOS current mirror 54 to force current generation via node 56 through device 28 and device 24. Likewise, the mirrored current in device 48 is also mirrored by NMOS current mirror 58 to force current generation via node 60 through device 30 and device 26. The mirrored current in device 46 provides a stable bias current for devices 24 and 26.

Finally, the current mirror **64** provides an ac path and a stable current supply, via lines **66** and **68**, to devices **28** and **30**, respectively.

The circuit **10** described above in Figure **1** is known, and provides good performance. In fact, the use of a Miller-compensating capacitor results in a multiplication of the effective compensating capacitance, enhancing the desirable, and known, effect of pole splitting. However, as the load capacitance on output node **36** increases, the Miller-compensating capacitor **C1** must also increase in value to maintain stability in the circuit **10**. This can result in capacitor **C1** occupying more physical space than is desired, or even than can be afforded.

Figure **2** is a schematic diagram of a differential amplifier **100** including a Miller-compensating capacitor **C2** provided in accordance with the principles of the present invention. Similar to the circuit **10** of Figure **1**, the amplifier **100** structure is two stage, the first stage **20'** being a folded-cascode differential amplifier, and the second stage **22'** being a Miller-compensated PMOS device amplifier. Unlike the circuit **10** of Figure **1**, however, Miller-compensating capacitor **C1** and resistor **R1** are not provided.

Instead, the circuit **100** of Figure **2** includes a novel capacitor arrangement consisting of capacitor **C2** connected between the output node **36'** and the common connection node **102** for the gates of the two NMOS devices—an NMOS device **104** diode-connected, and an NMOS device **106** ratioed by a factor of ten as compared with device **104**, comprising current mirror **54'**. By connecting capacitor **C2** in this way, the feedback current flowing through capacitor **C2** is amplified, i.e. multiplied by, e.g., ten by current mirror **54'** before reaching the high impedance node **68**. The resulting load capacitance seen by the high-impedance node **68** is then ten times greater than the Miller-multiplied version connected using prior art principles. Thus, there is provided by the present invention a multiplication of an effective capacitance that is itself a multiplied, effective capacitance.

Note that the value ten for the multiplication factor described above is arbitrary, and is selected for example only. The gain, and thus the multiplication

factor, is ultimately achieved in the circuit of Figure 2 by the effective current amplification by current mirror 54', and its limitation depends on the physical restrictions, or spread, of current mirror 54'. In the circuit of Figure 2 the mirror ratio of the current flowing through current mirror 54', i.e., the ratio of the widths of device 106 and device 104, and thus the ratio of the current flowing through device 106 as compared with device 104, is ten. Other ratios, and thus other capacitance multiplication factors are possible. The width of PMOS device 44 is reduced by the same ratio. For optimal matching performance (low input offset), PMOS device 48 and current mirror 58 are made to match PMOS device 44 and current mirror 54.

Key is the amplification of the compensating capacitor's current.

Figure 3 shows an ac-equivalent model 200 of the amplifier circuit of Figure 2. The model 200 has two stages, a first stage 210 and a second stage 220. As shown, in first stage 210 a differential input voltage V_{in} ($V_{in} = V_p - V_n$) produces a current of $g_{m1}V_{in}$ in equivalent transconductor 212. In the second stage 220, a voltage V_x is seen at the input of Miller-compensating capacitance C_m and an ac current I_x flows through internal resistance R_i . The current I_x is reflected back through block 214, multiplied by ten, to the input circuit 210.

The transfer function of the circuit model 200 of Figure 3 may be derived as follows:

$$\text{Eq. 1} \quad I_x = (V_o - V_x)C_ms$$

$$\text{Eq. 2} \quad V_x = \frac{V_o R_i C_ms}{1 + R_i C_ms}$$

$$\text{Eq. 3} \quad V_o = - \{ [V_{in} g_{m1} + 10 I_x] r_{g_{m2}} + I_x \} R_o$$

Combining Equations 1, 2 and 3 yields:

$$\text{Eq. 4} \quad \frac{V_o}{V_i} \equiv \frac{-(g_{m1} r_{g_{m2}} R_o)(1 + R_i C_ms)}{1 + C_ms(R_i + 10 r_{g_{m2}} R_o)} \approx \frac{-g_{m1} r_{g_{m2}} R_o (1 + R_i C_ms)}{1 + C_ms 10 r_{g_{m2}} R_o}$$

Note in Equation 4 that there is no right-hand plane zero. In fact, a Left Hand Plane (LHP) zero is inserted. This LHP zero can be used to optimize the compensation of the loop in Figure 2 created by the connection of capacitor C2 between the output node 36' in the second stage 22' and the common gate connection of devices 104 and 106 in the first stage 20', which is controlled by the transconductance of device 104. The dominant pole for the circuit 100 of Figure 2 is defined by the high impedance node 68 and ten times the gain of the second stage 22' times the Miller-compensating capacitance C2. For instance, the LHP zero can be designed to lie approximately where the pole of output node 36' lies. As a result, the pole is cancelled and phase margin is consequently increased.

Figure 4 is a graph showing Bode plots of the behavior of different circuits like the circuit shown in Figure 1 and the circuit shown in Figure 2. This figure helps in understanding the principles presented in the immediately preceding paragraph. Two different sets of curves 236, 238, are shown in Figure 4. As can be seen, while there is one horizontal axis 230, representing frequency and divided into units of Hertz, there are two vertical axes, a first axis 232, representing the gain of the respective circuit and divided into units of decibels ("DB"), and a second axis 234, representing the relative phase of the output signal as compared with the phase of the input signal, and divided into units of degrees. The first set of curves 236 is plotted against the gain axis 232, while the second set of curves 238 is plotted against the phase shift axis 234. In the set of curves 238 a zero relative phase compared with the input is 0°, which is the same as 360°. In all of the circuits represented in Figure 4, as frequency increases the phase of the output signal tends to lag more, as compared with the phase of the input signal, and thus it will be noted that the curves 238 all tend to drop, showing a decrease in phase from 360° as frequency increases. In addition, in all of the circuits represented in Figure 4, as frequency increases the gain tends to drop, and thus it will be noted that the curves 236 all tend to drop, showing a decrease in gain as frequency increases.

A first curve **240** is a plot of the gain of a representative circuit constructed like that of Figure 1, against frequency, in which the compensating-capacitance **C1** is 2 pF. A second curve **242** is a plot of the relative phase of the output signal V_o as compared with the phase of the input signal $V_{in} = V_p - V_n$ for the same circuit. Note that at the frequency at which the unity gain point **244** exists for curve **240** the relative phase, shown by point **246**, is approximately 140° , which represents a phase shift of -220° , or 40° more than the -180° limit for stable operation.

A third curve **248** is a plot of the gain of a representative circuit constructed like that of Figure 1, against frequency, in which the compensating-capacitance **C1** is 20 pF. A fourth curve **250** is a plot of the relative phase of the output signal V_o as compared with the phase of the input signal V_{in} for the same circuit. Note that at the frequency at which the unity gain point **252** exists for curve **248** the relative phase, shown by point **254**, is approximately 200° , which is a phase shift of only -160° , which is within the -180° limit for stable operation.

Now, a fifth curve **256** is a plot of the gain of a representative circuit constructed like that of Figure 2, against frequency, in which the compensating-capacitance **C2** is 2 pF. A sixth curve **258** is a plot of the relative phase of the output signal V_o as compared with the phase of the input signal V_{in} for the same circuit. Note that at the frequency at which the unity gain point **260** exists for curve **256** the relative phase, coincidentally also shown by point **260**, is approximately 270° , which is a phase shift of only -90° , which is well within the -180° limit for stable operation. In fact, stable operation continues well beyond the unity gain frequency. Thus, the extension of curve **258** in the manner shown so as to increase the phase margin shows how the LHP zero can be placed strategically so as to enhance the stability of the circuit of Figure 2.

The technique may also be extended to simple compensated amplifiers that do not have Miller-compensating capacitance. Figure 5 illustrates one such implementation. In this instance, the technique is used to effectively multiply the

compensating capacitor C. NMOS device MN2 is ten times larger than NMOS device MN1, providing a multiplication factor of eleven; current I_x is sensed by MN1 and multiplied by ten by MN2. Thus, the effective capacitive current is

$I_x + 10I_x$, hence the multiplication factor of eleven, again a factor chosen arbitrarily.

A LHP zero is also inserted in this embodiment. The resulting transfer function, illustrated by the ac-equivalent circuit model shown in Figure 6, is roughly:

Eq. 5

$$\frac{V_{out}}{V_{in}} \approx \frac{-g_{mp1}(r_{ds-MP1} // r_{ds-MN2}) \left(1 + \frac{C_s}{g_{MN2-MN1}} \right)}{1 + s(11C)(r_{ds} // r_{ds-MN1})}$$

where Equations 1 and 2 still apply. Note that in Figure 6

$$r_{ds} = r_{dsMN2} // r_{dsMP1}.$$

Finally, note that while the circuits disclosed herein are all made of MOS devices, the principles are applicable as well to circuits made of bipolar devices. For example, a bipolar current mirror could be used as a current amplifier in much the same way as the NMOS current mirror 54' of Figure 2, to provide the effective multiplication of capacitance.

Although the present invention and its advantages have been described in detail, as well as some variations over the disclosed embodiments, it should be understood that various other changes, substitutions and alterations can be made herein without departing from the spirit and scope of the invention as defined by the appended claims.